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Estimating Burst Swim Speeds and Jumping Characteristics of Silver Carp (*Hypophthalmichthys molitrix*) Using Video Analyses and Principles of Projectile Physics

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PURPOSE: The purpose of this report is to present preliminary data regarding the use of videography to estimate Silver Carp burst swimming speeds. The authors document the use of videotaped Silver Carp leaping behavior as a means of estimating, in-situ, burst swimming speeds, fish leap height, and horizontal distance traveled during a leap.

SUMMARY: Hydraulic and vertical barriers to Silver Carp dispersal can be developed if maximum burst speeds and jump characteristics are quantified. Using videography of jumping fish (N = 27), representing four populations of Silver Carp, burst speeds were estimated using direct time-lapse technique as 5.30-8.39 m/s, equivalent to 8.16-11.30 body lengths per sec (BLS). Applying principles of projectile physics to a subset of those fish (N=4), burst speeds were estimated as 7.78-9.74 m/s, angle of leap as 44-70º, and height of leap as 1.81-2.24 m. Mean burst speed for this subset (8.56 m/s) approximated that of direct measurement (8.16 m/s) suggesting that principles of projectile physics provide useful estimates of empirical burst speeds. Data suggest that dispersal of comparably performing Silver Carp would be restricted by water velocities > 10 m/s and vertical drops > 3 m. Effective barriers to dispersal of the species, however, require data on variation in swimming and jumping performance and how those data relate to size and morphology of individual fish.

BACKGROUND: Silver Carp – This Asian fish was first introduced into the United States in the 1970s, and has subsequently spread into many watersheds in the northern, eastern, and southern regions. According to Kolar et al. 2007, Silver Carp are firmly established in the Mississippi River and there is significant concern among scientists regarding the potential of this species to out-compete and eliminate native species wherever they are located. Although efforts to prevent range expansion are on-going, unfortunately the species continues to spread across the U.S. Silver Carp are highly vagile due to their ability to leap high into the air and their powerful swimming capabilities.

At present, various methods have been proposed and implemented to prevent Silver Carp from extending their range (Conover et al. 2007). Methods that involve physical barriers (hydraulic, vertical, or electric) to inhibit movement require estimates of swimming ability in order to evaluate their potential efficacy. Maximum burst swimming speeds (i.e., the maximum possible speed at which a fish can swim) and leaping trajectory (i.e., height and angle of jump), are notoriously difficult to measure in the laboratory. However, these attributes are critical when considering whether an invasive species can traverse a particular barrier (e.g., flow field, drop structure, or electrical array). For this reason, it is extremely important to accurately quantify their swimming and leaping characteristics.

Applications of Swim Speed Data - Accurate burst swimming speed estimates are crucial for a variety of applications, especially when the alteration of natural stream and river flow is being considered. Clearly, alterations of water flow, both quality and quantity, may inhibit fish passage. Increases in flow rate that approach mean burst swim speeds can impede or totally prevent fish passage. In most cases, design considerations are typically implemented to provide for successful fish passage, and the majority of research work completed has addressed this topic. For example, Baker and Votapka (1991) considered the problems faced by fish when encountering highway culverts. Cada (2011) reported on modifications of hydroelectric turbines that would allow juvenile fish to survive passage. In contrast to the above, knowledge of fish burst swimming speeds coupled with mechanical and electro-mechanical barriers can be used to prevent range expansion of invasive species. Electro-mechanical weirs have played an important role in the attempts to control Sea Lamprey, *Petromyzon marinus* populations in the Great Lakes (Hunn and Youngs 1980). Similarly, electric barriers in the Chicago Sanitary and Ship Canal have been erected to prevent the movement of Silver Carp into Lake Michigan (McInerney et al. 2005; Holliman et al. 2015). However, concern exists that burst speeds of Silver Carp could create enough forward momentum to carry stunned fish through the electric barriers and that fish may be able to leap over vertical drops at river structures.

Measuring Swimming Performance - Swimming performance is typically studied using swim tunnels (e.g., Parsons, 1990; Parsons et al. 2003; Hoover et al. 2011; Hoover et al. 2012). Swim tunnels are appropriate for determining swim speeds that are sustained (> 200 min endurance), prolonged (0.5 to 200 min endurance), or critical (variable endurance, typically between 5 and 60 min). However, burst swimming speeds (< 0.5 min) estimated in swim tunnels can be under-estimated. Confinement of the fish to the working section of the tunnel may limit its ability to reach burst speeds by limiting the swimming strategies available to the fish. Even large tunnels (> 1500 L working section) restrict or prohibit burst-and-coast, swim-and-glide, and aerial behaviors (sensu Fish, 2010). Therefore, burst speed estimated from tunnel studies may be a combination of the maximum flow rate generated and the expression of a sub-set of fish swimming behaviors (e.g., station holding, drifting, and slow, linear free-swimming). In addition, Silver Carp are "sensitive," becoming sluggish or even catatonic when confined to small volumes of water, even with judicious handling. Measuring burst swimming speeds *in-situ* using alternative methods eliminates the stress of capture, holding, handling, and other limitations to performance caused by swim tunnel confinement and would be preferable to traditional laboratory swim studies.

Two alternative methods, both based on videographic analyses, have been used to successfully estimate swim speeds. Rohr et al. (2002) estimated maximum swim speeds of videotaped, captive, and free-ranging dolphins, Delphinidae, by timed sequential analyses of video frames. Brunnschweiler (2005) used projectile physics to estimate the speed (ca. 6.3 m/sec) of Blacktip Sharks, *Carcharhinus limbatus* from videotape to document the angle and height of their leaps.

OBJECTIVES: Our intention in this study was to examine on-line videotaped Silver Carp leaps and use these videos to estimate the swim speeds and leap characteristics of carp as they exit the waters' surface. We used both direct estimates of swim speeds as well as indirect estimate speeds based on projectile physics. These values are assumed to be a reasonable approximation of the burst speeds of these fish.

METHODS: Videos were downloaded from the internet and when available, the location and date of when the videos were produced was noted. Only those video segments that demonstrated clear jumps were analyzed during the study. Typically, carp sizes were estimated from those fish that landed in the boat. Various reference objects (i.e., soda bottle, ice chest, etc.) of known size that appeared in the same video frames along with the fish were used to estimate fish size. Videos were down-loaded into *Windows Movie Maker* and *Virtual Dub* for analysis which allowed frame-by-frame observations. Typical videotape runs at 30 frames/sec therefore, each frame represents 0.033 seconds. In many cases, carp were observed just breaking the surface of the water and then the number of frames, and thus the time required, for the tail to exit was measured (Figure 1).

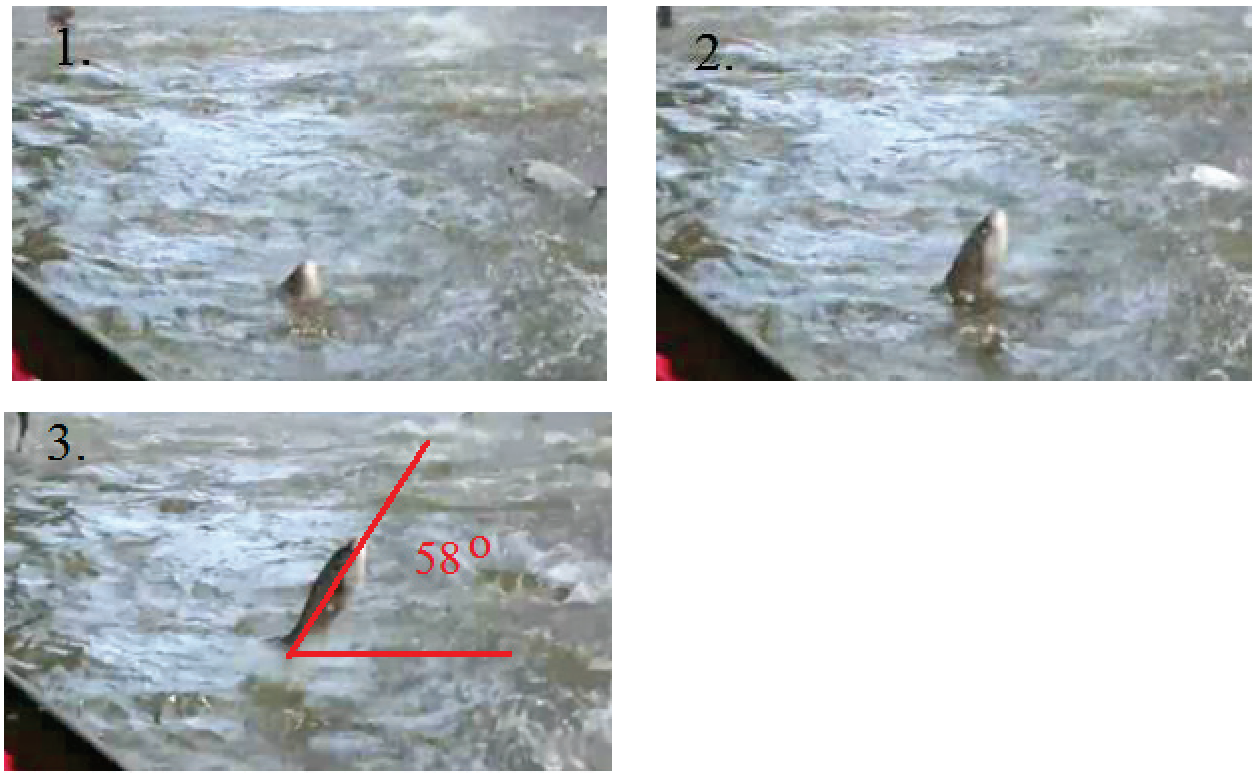

Figure 1. Three frames of the Wabash River video showing a Silver Carp leap. (1.) The nose of the fish has just appeared above the surface of the water. (2.) Approximately half of the body length has emerged. (3.) The tail of the fish has cleared the waters' surface. The sequence required 0.099 seconds and the fish leapt at an approximate 58^{o} angle.

For absolute swim speed estimates, we measured fork length (FL) from the videos. This measurement was easily observed in the videos over total length (TL). We then converted FL into TL using an original regression model for fishes in the Lower Mississippi River (LMR) (Figure 2). In some instances, it was impossible to estimate the length of individual fish that were observed leaping and for those cases we used a default value for size. This default value was the mean measured length of five fish that jumped into a boat during a field study in the LMR in September 2013. Those fish ranged in size from 648–845 (mean = 743 mm TL) (equivalent to 551–728 mm FL).

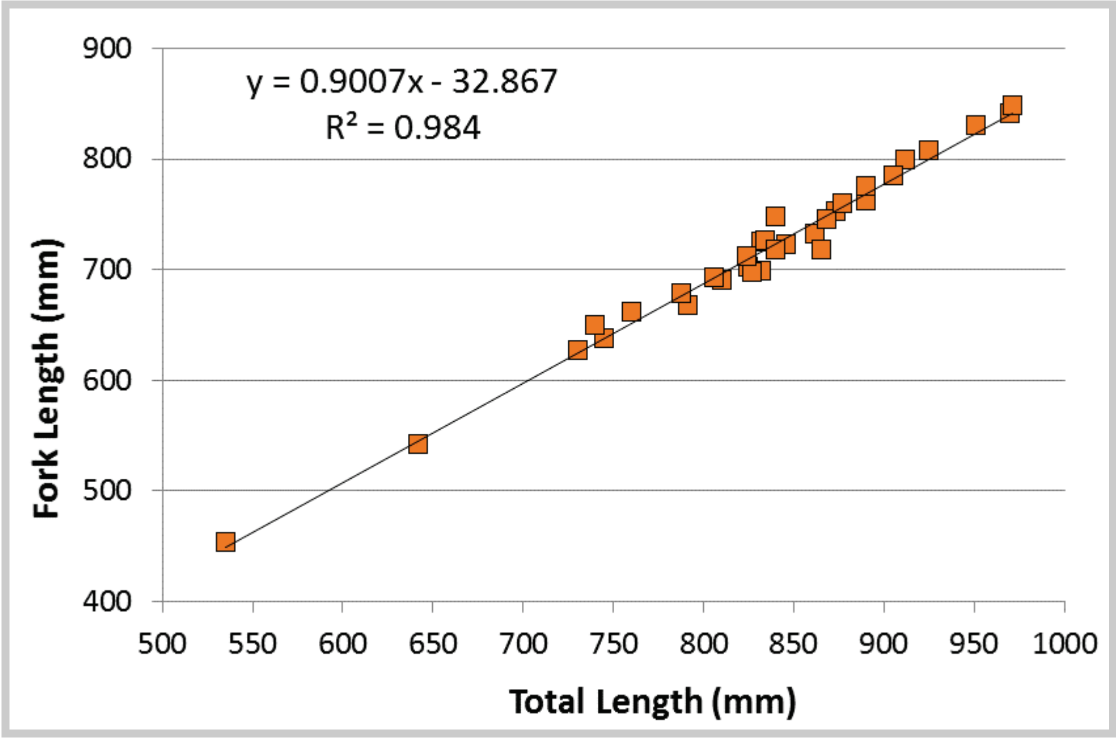

Figure 2. Relationship between total length and fork length of Silver Carp (red squares). Fish were collected June 2015 from Forest Home Chute, a side channel of the Mississippi River, near Vicksburg, Mississippi.

In addition to the above method, we also used the equation reported by Brunnschweiler (2005) to estimate swim speed. The equation to calculate the speed of a projectile

$$v = (h + \tfrac{1}{2}\, gt^2)/\ t \sin a \qquad (1)$$

was used to estimate burst swim speed where

v = speed (meters/s)

h = height (meters)

g = the acceleration of gravity (9.8 m/s)

t = duration of the leap (seconds)

a = leap angle.

Additionally, we estimated the horizontal distance traveled during a leap using the equation

$$x = v(\text{cosine } a)\ t \qquad (2)$$

where

x = horizontal distance traveled (meters)

v = initial velocity (m/s)

a = leap angle

t = duration of the leap (seconds).

To use these equations, the height and angle of the leap as well as the duration of the leap were measured directly from the video. These values were more difficult to obtain from on-line videos and thus fewer estimates using this method were possible. Height of the leap was estimated from the total length of the fish and the distance from the water's surface to the peak of the fishes' leap. Speeds were calculated using mean fish sizes estimated as described above. We estimated the total length of four fish from the Wabash River (WR) using Figure 1, and then used equation (1) reported by Brunnschweiler (2005) to estimate absolute swim speeds.

RESULTS: Direct Estimates of Swim Speeds from Video: Burst swimming speeds were successfully estimated for fish from four bodies of water: the WR, the Illinois River (IR), the Middle Mississippi River (MMR) near St. Louis, Missouri, and the Upper Mississippi River (UMR) from Pool 26 at the Great Rivers Field Station (GRFS) of the Illinois Natural History Survey, Brighton, Illinois (Table 1). Mean burst swim speeds ranged from 5.30 to 8.39 m/s (8.16 to 10.94 body lengths per second [BLS]) with the highest swim speeds observed in the IR. Because of difficulty in estimating fish length in the MR and GRFS videos, we used our default length of 743 mm TL for fish from the LMR to estimate all swim speeds for those water bodies. For this reason, statistical tests for significance were conducted on only the WR and IR estimates. An ANOVA significant ($P = 0.00081$; $F = 4.96$; $DF = 1, 10$) difference was observed when absolute swim speeds for the WR and IR were compared. However, no significant difference was observed when relative swim speeds were compared nor was there a difference when total lengths were compared for the WR and IR.

Table 1. Burst swim speed estimates measured directly from videotape of Silver Carp from four water bodies. Wabash River (WR) absolute swim speeds were significantly different ($P = 0.0008$, $F = 4.96$) than those values for the Illinois River (IR). Middle Mississippi River (MMR). Upper Mississippi River (UMR).

	Wabash River	**Illinois River**	**MMR**	**UMR**
Speed (m/s)	5.30 ($\pm$0.61)$^{(s)}$	8.12 ($\pm$0.64)$^{(s)}$	8.39	8.13
Speed (BLS)	8.16 ($\pm$0.60)$^{(ns)}$	10.45 (+1.45)$^{(ns)}$	11.3	10.94
Mean TL (mm)	650 ($\pm$28.1)$^{(ns)}$	777 (+61.1)$^{(ns)}$	743 [1]	743 [1]
N	7	5	8	7
Date	05/08/13	NA	09/31/10	NA

1 Default estimate for length based on measurements of five jumping fish collected September 2013 from the Lower Mississippi River near Vicksburg, Mississippi.

Estimates of Swim Speeds and Leap Characteristics Using Principles of Projectile Physics*:* Fish measurements made from the WR video, resulted in fork lengths ranging from 569 to 711 mm (mean = 569) and total lengths ranging from 668 to 826 mm (mean = 747) (Table 2). Fish exited the waters' surface at angles of 44° to 70°, remained aloft for 0.83 to 1.30 seconds, and rose to heights of 1.87 to 2.24 meters (Table 2). Using average total length and those leap characteristics, the burst swimming speed was estimated and ranged from 7.78 to 9.84 m/sec (mean = 8.56). Using those velocities, fish were estimated to cover horizontal distances of 2.81 to 5.82 meters during a leap.

Table 2. Characteristics of Silver Carp leaps and estimates of carp burst speeds. Data obtained using projectile physics from Wabash River (WR) fish videotaped on 8 May 2013. FL = fork length, TL = total length, H. = horizontal. Values below the lower line are mean values for each metric.

Mean FL (mm)	Mean TL (mm)	Height (meters)	Duration (seconds)	Angle of Leap (degrees)	Speed (m/s)	H. Distance (meters)
569	747	2.24	1.06	70	7.78	2.81
569	747	2.05	1.30	64	8.85	5.05
569	747	1.87	1.06	62	7.88	3.92
569	747	2.24	0.83	44	9.74	5.82
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DISCUSSION: Silver Carp, like the freshwater hatchetfishes (Gasteropelecidae) and marine flying fishes (Exocoetidae), are morphologically adapted and behaviorally predisposed for leaping. Hatchet fishes, typically < 10 cm TL, and flying fishes, typically 15 to 50 cm TL, have a large lower caudal lobe and expansive wing-like pectoral fins, which, respectively, enable the fish to generate thrust for high speed swimming when the body is above water level, soar high into the air, and to glide long distances (Nikolsky, 1963; Davenport, 1994). Anecdotal reports for flying fishes suggest extraordinary flights of hundreds of meters (Boulenger, 1925; Marshall, 1970). Quantitative studies indicate burst speeds of 9 to 18 m/s, heights of 2 to 8 m, and distances of 9 to 100 m (Shoulejkin, 1929; Gray, 1953; Marshall, 1970; Davenport 1994). Silver Carp, typically 50 to 100 cm, are many times more massive than flying fishes, with small pectoral fins, but possess a ventral keel and enlarged lower caudal lobe (Figure. 3). Consequently, their performance as swimmers and leapers is lower: burst speeds of 6.7 to 9.7 m/s, heights of approximately 2 m, and distances of approximately 3 to 6 m (Tables 1 and 2). Hydrologic containment of Silver Carp by managing flow fields and vertical drops at structures, then, is not unrealistic.

Previous estimates of burst speeds in fishes have employed a variety of methods. For example, Videler and Wardle (1991) measured maximum burst speed (mean = 10 BLS, maximum = 18 BLS or 5.5 m/s) of a 30.5 cm mackerel using a high-speed camera. Block et al. (1992) used telemetry to measure bursts of swimming activity as high as 2.25 m/s in blue marlin. Castro-Santos (2005) measured “sprint” (= burst) speeds of six migratory fish species using a hydraulic flume and reported speeds of 1.5 to 4.5 m/s.

Figure 3. Silver Carp female from the Lower Mississippi River, collected 9 Jun 2015, 846 mm TL, 5.15 kg, and used in swimming endurance test (caudal margin was frayed during conduct of test). Lower caudal lobe is conspicuously larger than upper caudal lobe (top) and mid-ventral keel is prominent (bottom). Both features are morphological adaptations for near-surface swimming and jumping.

Documented burst speeds of Silver Carp, using traditional techniques, are ambiguous. Swim tunnel studies, in the laboratory and in the field, indicate burst speeds of 7.7 BLS for juveniles (100 mm median TL), 6.0 BLS for sub-adults (214 mm median TL), and < 4 BLS for adults (713 mm median TL) (Hoover et al. 2012; Hoover, unpublished data). Such measurements, however, have limited and tenuous application to fish swimming freely in an open water environment. Field studies of a telemetry-tagged fish (460 mm TL) in China suggest a maximum speed of approximately 10 BLS (Konagaya and Cai, 1987). This study was based on a single observation of a single fish with overwhelming majority of data documenting volitional swim speeds < 3 BLS. Alternative methods that provide greater accuracy and consistency in results are needed to clarify just how fast carp can swim.

There have been few attempts to estimate fish swim speeds using videotape of fish leaps. The difficulty in using videotape to estimate burst speeds is in obtaining enough leaps to capture swim speed variability and making reproducible measurements directly from the video. Fish leaps are, in general, a relatively rare event and the vast majority of fishes rarely, if ever, leap. This problem was noted in the work by Brunnschweiler (2005) where in over ten hours of observations only three blacktip shark leaps were captured on video. In contrast, Silver Carp make spectacular leaps, are easily stimulated to leap, and tend to leap *en masse*. This behavior is relatively unusual in large fish such as Silver Carp, and has generated a seemingly limitless supply of on-line, videotaped, often high-definition, Silver Carp leaps.

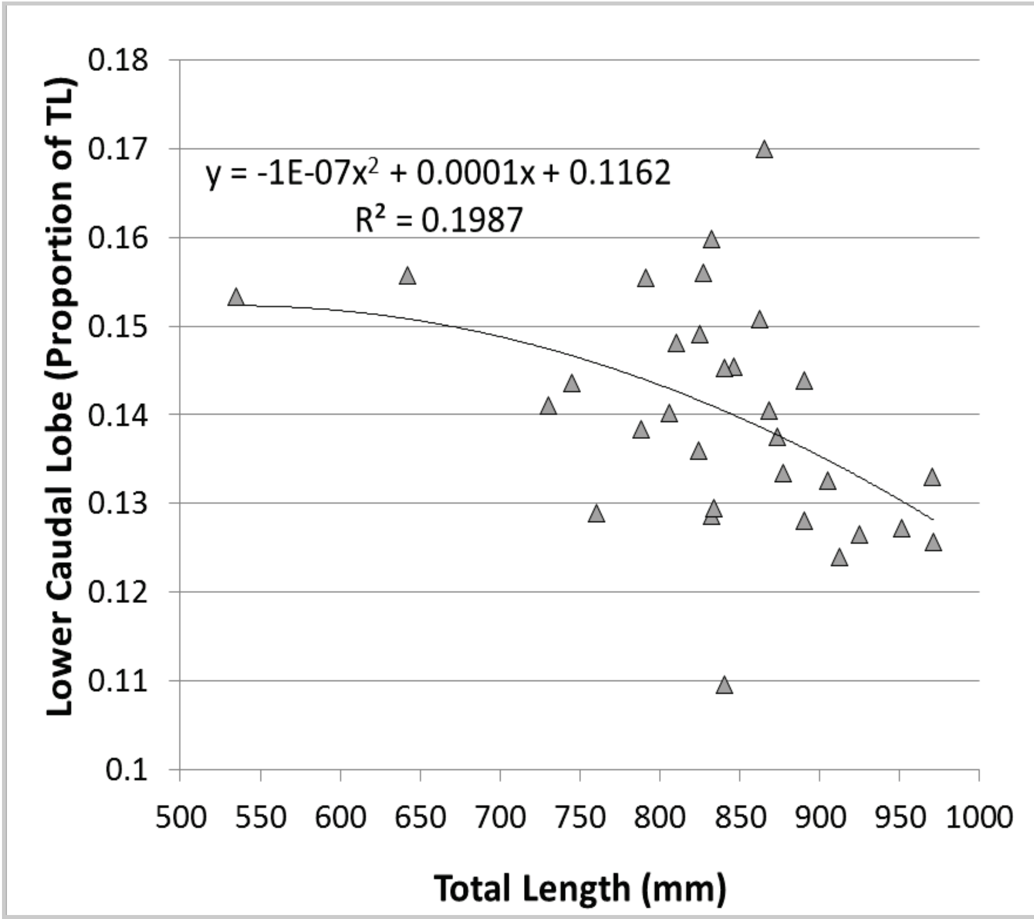

Figure 4. Relationship between total length and length of lower caudal lobe of Silver Carp (gray triangles). Fish were collected June 2015 from Forest Home Chute, a side channel of the Lower Mississippi River, near Vicksburg, MS.

Our direct estimates of burst swimming speed from videotape for Silver Carp suggest that these are highly active fishes. Burst swim speeds ranged from 5 to 8 m/s and 8 to 10 BLS. The IR estimates were significantly higher than those for the WR and an explanation for this is not readily apparent. The larger mean size for IR fish could explain the absolute burst speed difference. However, the fact that this size difference was not statistically significant does not support this conclusion.

In addition to direct estimates of burst swim speeds from videotape of fish leaps, if the angle, height, and duration of the leap can be determined, an additional estimate of speed can be obtained. As noted above, Brunnschweiler (2005) estimated blacktip shark, *Carcharhinus limbatus* speeds of about 6.3 m/s using projectile physics but videotaped few fish. In this report, we were able to review video of many hundreds of leaping silver carp, and thus only those leaps whose characteristics were clearly defined and easily measured were used. It is noteworthy that burst speeds estimated in this way were similar to those obtained using direct measurements. Burst speeds of about 8 to 10 m/s (10.4 to 11.0 BLS) suggest a relatively active fish and, other than the 18 BLS (5.5 m/s) for the small mackerel reported by Videler and Wardle (1991), the values reported here are among the highest reported for any fishes. It is likewise interesting and significant that Silver Carp are estimated to be

able to leap a maximum height of 1.87 to 2.24 meters and cover horizontal distances of 2.81 to 5.82 meters.

The values reported herein should be considered first approximations of Silver Carp burst swim speeds and leap characteristics, and *in-situ* validation of our estimates is called for. Caution is indicated in the interpretation of these data since these are first approximations. Season, body condition, reproductive state, prior experiences of the fish, and environmental conditions will all influence physiological state and thus swimming speeds. In addition, morphology of Silver Carp may vary substantially among individuals, size classes, and populations. For example, size of the lower caudal lobe in Silver Carp ranges from 11% to 17% of the total length of adult fish, declines significantly with size of fish, but is also highly variable within a narrow range of fish sizes (Figure. 4). Variation in this morphological feature alone could substantially influence thrust (burst speed) and lift (jumping) in a surface swimming fish. Estimates of swimming and jumping characteristics, to be accurate, would need to include specimens exhibiting the full range of caudal lobe sizes.

To assess the risk of Silver Carp invasions into new waterways and to prevent invasions, managers must be able to evaluate and create physical barriers to passage: hydraulic, vertical, and electrical (Conover et al. 2007). For such risk assessments to be certain and for management to be effective, accurate estimates of Silver Carp burst speed, jumping height, and jumping distance are needed. At present, such information is largely speculative or based on limited data. Empirical studies of Silver Carp are needed in which swimming and leaping performance is rigorously quantified and in which influences of confounding variables, intrinsic (e.g., fish size and morphology) and extrinsic (e.g., water temperature and depth), are described.

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